FLOW FIELD CHARACTERIZATION INSIDE AN ARTERIOVENOUS GRAFT-TO-VEIN ANASTOMOSIS UNDER *PULSATILE FLOW* CONDITIONS

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Abstract - *The purpose of this study was to investigate the relationship between the distribution of turbulence intensity and the localization of stenoses inside the venous anastomosis of arteriovenous (A-V) grafts. Turbulent flow measurements were conducted inside an upscaled end-to-side graft model under pulsatile flow condition. The pulsatile flow waveforms had maximum, minimum and mean Reynolds numbers of 2500, 1200 and 1800, respectively based on the graft diameter. The distribution of the velocity and turbulence intensity was measured at several locations in the plane of the bifurcation of the model. Turbulence intensity was found to be greatest downstream of the anastomosis.*

KEYWORDS: *Arteriovenous graft, dialysis, turbulence, stenosis*

I. INTRODUCTION

Computational [3,5] and experimental [2,7] investigations of the fluid dynamics of distal end-to-side anastomoses associated with arterial bypass grafts have been conducted, motivated by the fact that this junction is a site of particularly high risk in intimal hyperplasia and other forms of arterial disease. A further motivation is that the junction offers a situation providing a complex mix of fluid dynamic phenomena and can potentially aid the quest for causal linkages between disease localization and fluid dynamic details for arteries in general.

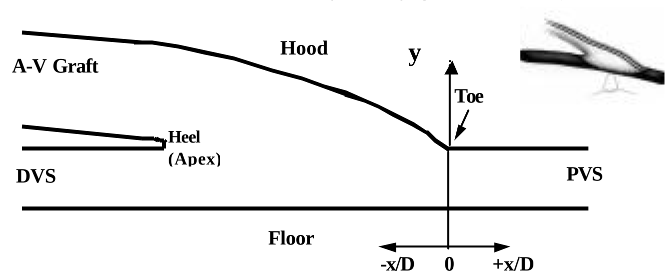
A similar geometry occurs at the downstream end of an arteriovenous anastomosis created by incorporation of a loop of graft material for the purposes of repeated high-flow-rate vascular access, as in renal dialysis. Similar experiences of intimal hyperplasia leading to loss of patency, but now in the vein rather than the downstream artery, have as in the arterial bypass graft situation led surgeons to experiment with a variety of detailed geometries when forming the end-to-side anastomosis between the graft and the vein. Reference [6] have shown that hyperplastic stenoses occur predominantly in the proximal vein segment (PVS), downstream of the graft-to-vein junction. This suggests the possible involvement of disturbances to flow created in the graft-to-vein junction and advected downstream.

To date there has been only one detailed set of investigations of the fluid dynamics of the graft-to-vein anastomosis [8]. Reference [8] obtained the mean velocity profiles and wall shear stresses (WSS) inside realistic A-V graft models. They implicated the low and oscillating WSS near the stagnation point and separation region in the development of a lesion distal to the toe (see Figure 1). No measurements of turbulence levels were reported. The first modeling study was done on the turbulence measurements quantitatively [1]. Reference [1] tried to understand the location of the wall shear stresses and turbulence regions inside an AV graft model under steady and pulsatile flow conditions.

Reference [4] measured perivascular tissue vibration and intimal thickening in A-V graft venous anastomoses, investigating in separate studies the results of varying both flow-rate and geometric details. They found the highest tissue vibration and intimal thickening to be localized on the toe side of the PVS. In the absence of direct measurements of flow turbulence, they hypothesized that tissue vibration was caused by turbulent flow and that the degree of the vibration was correlated with the blood turbulence level.

While these studies have contributed to our understanding of the intimal hyperplasia formation in the anastomosis they did not fully take into account all of the special fluid mechanical circumstances pertaining to this junction. The major differences between these two end-to-side anastomoses, the arterial and the venous, from the fluid mechanical point of view, relate to the higher flow-rate and the reduced viscosity for the renal dialysis access graft. Higher flow-rate is a consequence of the fact that the arteriovenous shunt bypasses the peripheral resistance, forcing the heart to increase cardiac output by virtue of the increased venous return. Unlike the arterial bypass graft, where the predominant resistance is peripheral, and the graft therefore does not set its own flow-rate, the arteriovenous graft does; its own resistance determines the shunt flow.

Reference [4] noted that higher Reynolds number implies a greater tendency to flow instability and turbulence. Whereas the arterial bypass junction is unlikely to be turbulent than the venous one to be. Evidence to support this reasoning is provided by the results of our own ultrasonic measurements of flow-rates and vessel diameters in a patient with such an arteriovenous graft, as reported below. We assume that turbulent flow is likely in any graft-to-vein junction



DVS: Distal Vein Segment

Fig. 1. Geometry and nomenclature of the venous anastomosis A-V graft model.

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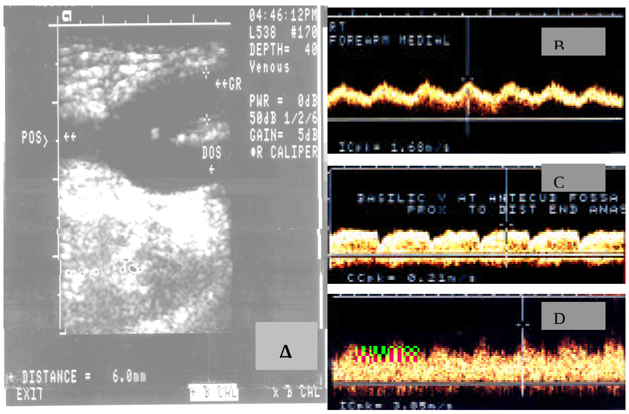

Fig. 2. Ultrasonic B-mode scan of a dialysis patient's graft-to-vein junction (A) and ultrasound velocity measurements in the graft (B), DVS (C) and PVS (D).

having the diameter and flow-rate necessary for continuing patency and dialysis use.

In this study, we report the measurements under pulsatile flow conditions of the magnitude and spatial distribution of turbulence inside an *in vitro* graft model representative of the graft-to-vein junction of a dialysis A-V graft.

II. METHODS

A. *In Vivo* Measurements

A-V graft-vein junction flow conditions and vessel diameters were determined using Color Doppler ultrasound measurements (Acuson 128XP/10) conducted on two dialysis patients. The measurements were conducted within one month of graft construction. Figure 2 shows the B-scan-mode outline of the venous anastomosis and the ultrasound velocity measurements in the graft, DVS and PVS respectively in one of the patients. The PTFE A-V graft connected the brachial artery to the basilic vein near the patient's elbow. As seen in Figure 2, the measured graft lumen diameter (D) for this patient was 6.0 mm; in the other patient it was 6.7 mm. In both patients, the PVS and DVS were of comparable diameter and somewhat smaller than the graft. The angle of between the graft and the vein was 45? in one patient and much smaller in the patient shown in Figure 2. There is considerable variation in the geometry from patient to patient for surgical reasons.

For the patient shown in Figure 2, the instantaneous mean of the sonograph trace was estimated to be 1.5 m/s at the maximum and 1.0 m/s at the minimum of the cycle. For the other patient, the corresponding numbers were 1.2 and 0.8 m/s. Measurements were also made in the PVS and DVS; however, determination of the mean velocity was difficult because of the degree of spectral broadening. Reynolds numbers for the graft are difficult to estimate, since the shape of the velocity profile is unknown and the sample volume did not cover the whole vessel lumen. Based on the velocity measured in the sample volume (V), and assuming normal blood viscosity (? = 3.5 mPa s), the above measurements lead to a systolic peak Reynolds number of 2700 and a diastolic minimum of 1800 for the patient shown in Figure 3 (Re = ?VD/?, where ? = blood density, 1.05 g/ml). For the other patient, the corresponding values are 2400 and 1600. Two assumptions are here implicit: 1) that the velocity profile is flat, and 2) that the patient has normal haematocrit.

B. Model Geometry

The model was scaled up eight times relative to the *in vivo* case. The model material was a transparent elastomer (Sylgard 184, Dow Corning), and the walls were thick enough that the model could be considered essentially rigid. The graft-to-vein diameter ratio was 1.6, with a graft lumen diameter of 50.8 mm and a host vein diameter of 31.75 mm. The graft axis intersected the host vein axis at an angle of 5?.

C. Measurements

1. Flow System and Flow rate for pulsatile flow

An experimental system was designed and constructed to provide the upscaled model with the proper inlet and outlet flow conditions. The fluid employed, a mixture of 42% water and 58% glycerine by weight, was chosen to match the index of refraction of the Sylgard model (n=1.41). This fluid had a refractive index of 1.41, a density of 1.16 g/ml, and a dynamic viscosity of 10-mPa s as measured by a Wells-Brookfield LVTDV-II spindle type micro-viscometer at 25?C. A $^1/_3$ HP centrifugal Teel split-phase pump provided the pressure head to drive the flow. The total flow-rate was measured by bucket and stopwatch. Clinical experience is that the vein distal to the graft-vein junction often occludes; when it remains patent the flow-rate is typically small (less than 10% of the total flow-rate into the venous anastomosis). The ratio of the graft inlet flow-rate to the DVS inlet flow-rate was here chosen to be 85:15. The DVS inlet flow-rate was measured by an ultrasound transit-time flowmeter (Transonic model T101). Since fluid viscosity depends sensitively on temperature, a heater/mixer in the downstream tank was used to keep the fluid temperature at 23±0.5?C during the experiments. The flow system is shown in the Figure 3. The model was placed in a flow circuit under pulsatile flow conditions such that flow entered the graft from a straight tube four meters long with an inner diameter of 50.8 mm.

2. Laser Doppler Anemometr (LDA)

Velocity profiles were obtained by measuring the particle velocities on the millimeter-spaced points along the bifurcation plane. Thirteen axial locations along the vein axis were examined, starting distally (upstream) at $x = -6.8D$ relative to the toe position, and extending proximally to $x = +3.6D$. The two components of velocity were measured simultaneously with a two-color laser system (DANTEC, mirror type F147/B073 model 5500A), which used a 350 mW argon-ion laser (blue = 488 nm, green = 514.5 nm). The two measured velocity components were in the plane of the bifurcation; the *u*-component was parallel to the vein axis and the *v*-component was perpendicular to it. The system consists of two Bragg cells, two photomultipliers with receiving optics and two electronic counters.

The particles used to scatter the laser light were 0.993 ?m diameter polymer micro spheres (Duke Scientific Corporation, Palo Alto, CA, cat. no. 4009B). The turbulence fluctuations and Reynolds

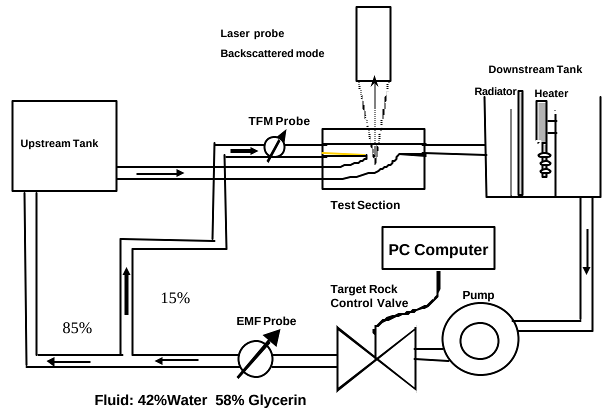

Fig. 3. Experimental flow system.

stresses were calculated as using a data processing algorithm for pulsatile flow written by Arslan [1]. All measurements were scaled to *in vivo* values ($V_{vivo}=2.5V_{vitro}$).

III. RESULTS AND DISCUSSIONS

The objectives of this research project was to characterize the flow field within the venous anastomosis of a dialysis patient's AV graft since fluid dynamics has been implicated as a cause graft failure. The flow field was examined in detail using LDA measurements inside an in vitro model of the venous anastomosis under pulsatile flow conditions. Figures 4 to 7 show the vector plot, fluctuation velocities in the direction of x (**u_{rms}**), fluctuation velocities in the direction of y (**v_{rms}**), and Reynolds stress (?u′v′**)** respectively. The results of this study show the flow field inside an AV graft to be complex and significantly different than that of an arterial by-pass graft. The velocity flow field was found to be both laminar and turbulent with a region of a separated flow which created a low WSS region at the toe side of the graft to vein connection. These velocity flow patterns may contribute to the development and localization of intimal hyperplasia.

The "M" shaped fluctuation velocity profiles were measured at the inlet of the graft at all phase angles. Within the anastomosis, turbulent levels were slightly higher value on the hood side. This is due slightly higher local Reynolds number on the hood side. The highest turbulent level was detected at the toe side of the PVS at all phase angles with the maximum occurring at x/D=+1.2. The highest velocity fluctuation was 12% of the local maximum mean velocity at the systolic peak at the location of x/D=+1.2 (see Figure 5-B). A second peak on the fluctuation profile was seen at systolic peak and deceleration at the floor side of PVS (see Figure 5.B and 6.B). The highest Reynolds stress measured was 1636 dynes/cm^2.

IV. CONCLUSION

Highly disturbed flow is associated with kinetic energy transfer as evidenced by vessel wall and perivascular tissue vibration. These stresses probably provide the stimulus that initiates and propagates the release of the biological mediators ultimately responsible of intimal hyperplasia formation.

The critical Reynolds stress reported in different studies varying from 2500 dynes/cm^2 to 30000 dynes/cm^2 [9]. Since there was no research done on turbulent and Reynolds stress estimation in AV graft quantitatively up to now. It is difficult to say if Reynolds stress values found in the present research may damage the RBC in the blood.

Further studies should be done on AV grafts with the different flow conditions and geometries together with the clinical studies to understand the affect of hemodialysis on intimal hyperplasia formation and graft failure.

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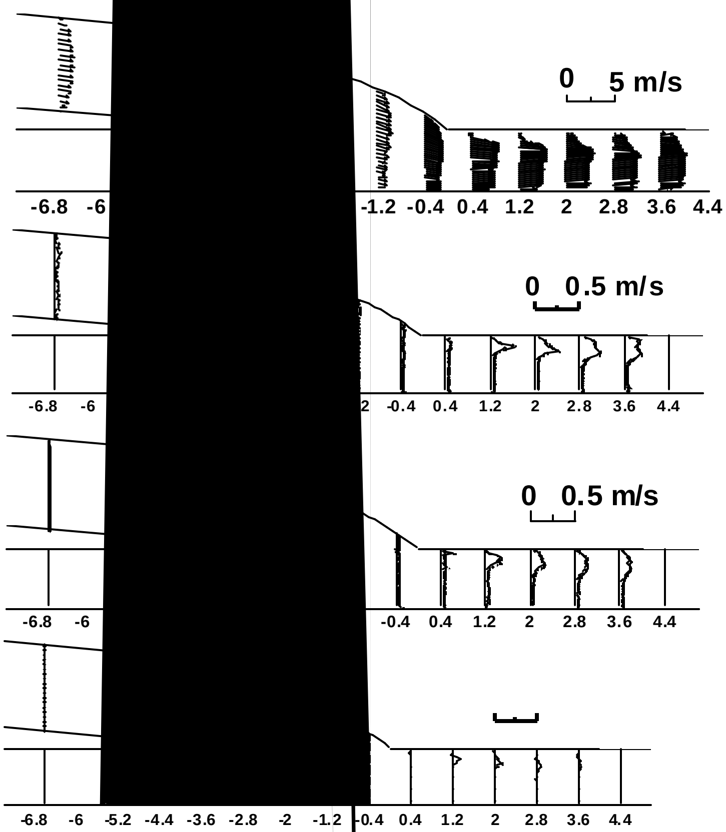
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